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ORIGINAL PAPER

# Growth response of broom (*Cytisus scoparius*) growing with and without radiata pine (*Pinus radiata*) seedlings to different P levels in soils

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**Abstract:** A study was carried out to test the effects of three rates of TSP (triple superphosphate) (0, 50, and 100 mg·kg$^{-1}$ P) on growth of broom with and without radiata pine seedlings and to determine the relationships between P concentrations in the broom shoot and dry matter yields with soil plant-available P (Bray-2 P). A bulk sample of soil was collected from Kaweka forest at soil depth of 0−10 cm, in New Zealand on March 11, 2001. The forest area was not supplied with fertiliser at least 30 years. The results show that TSP application increased P availability in the soil. The P availability concentration in soil of broom with radiata pine seedlings was higher than that in soil of broom alone. Bray-2 P concentrations had a significant logarithmic relationship with P concentrations of broom shoot and an exponential relationship with dry matter weight of whole broom plant.

**Keywords:** growth response to P fertiliser; *Cytisus scoparius* L.; *Pinus radiata*

## Introduction

Broom (*Cytisus scoparius* L.), a leguminous understorey, is one of New Zealand's important weed species found in radiata pine (*Pinus radiata*) plantations. This understorey has escaped from cultivation and aggressively invaded not only radiata pine plantations but also other many plantations. Broom seedlings can outcompete radiata pine seedlings and retard reforestation in many forest plantations (MacLaren 1993; Roy et al. 1998; Watt et al. 2003a). This weed species adapt the dry climate, with small deciduous leaves (Peterson & Prasad 1998). Moreover, this woody legume can grow throughout the year on sites where are wet with a mild winter (Fogarty & Facelli 1999), and reach 4 m in height (Peterson & Prasad 1998).

Weed control using herbicides is recommended in the establishment of radiata pine plantations as many studies showed that the presence of understorey vegetation resulted in significant reduction in the growth and survival rate of the trees. These negative effects are probably due to the competition of understorey vegetation with radiata pine for water, nutrients and light (Gadgil et al. 1992; Clinton et al. 1994; Richardson et al. 1996; Mason & Milne 1999; Watt et al. 2003b). On the other hand, several studies suggested that understorey vegetation may have beneficial effects on nutrient cycling and conservation within forest stands, which depends on the types of understorey species (Zou et al. 1995; Condron et al. 1996; O'Connell & Grove 1996; Binkley et al. 2000). Understorey vegetation can have an important effect on nutrients uptake for radiata pine trees, both before and after canopy closure. After canopy closure, the trees may uptake nutrients from the dead broom, especially in N-deficient sites.

A study on P concentrations of needles in 3-year-old radiata pine trees in a Pumice Soil (Yellow-brown loam) at Rotorua showed that P concentration increased significantly in radiata pine needles (Richardson et al. 1996). Meanwhile, other studies showed that conifers increased P availability (inorganic P, Olsen P and Bray P) in the soil (Davis, 1995; Condron et al. 1996; Chen et al. 2000; Scott 2002; Chen et al. 2003); hence, this increase in P availability may give an influence on P nutrition of weeds. However, Richardson et al. (1996) did not report whether radiata pine also affected P concentration in soil and weeds, because there was no plot with only weeds in their trial.

Studies were conducted particularly on physiology and population dynamics of broom (Partridge 1992; Nielsen et al. 1993; Parker 2000; Paynter et al. 2003). However, only a little information is available on the effects of fertiliser applications on broom, especially the addition of P fertiliser (Williams 1981; Tabard 1985). In radiata pine plantations, most soils are P deficient or

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marginally deficient, although P is an important nutrient (Hunter et al. 1991b). In this regard, a better understanding of the soil available P is required especially when broom grew in association with radiata pine trees. The information is useful for a better management of P fertilizer in the forest plantations. The objectives of this study were to investigate the effect of three rates of TSP (triple superphosphate) (0, 50, and 100 mg·kg$^{-1}$ P) on growth of broom with and without radiata pine seedlings.

## Materials and methods

### Experimental design

This trial pot with radiata pine seedlings (with and without the tree seedlings) was supplied with three rates of P fertiliser: 0, 50, and 100 mg·kg$^{-1}$ in soil (equivalent to 0, 50 and 100 kg·ha$^{-1}$, bulk density is 1 mg·m$^{-3}$, depth is 10 cm). The P fertiliser was applied as TSP (granules ground to pass through 250 µm; total P is 20.7%). The treatments were replicated five times in a completely randomized factorial design in a glasshouse at maximum and minimum temperatures of 28ºC and 13ºC respectively.

On March 11, 2001, a bulk sample of soil was collected from soil depth of 0–10 cm at Kaweka forest, in New Zealand. The forest area was not applied with fertiliser at least 30 years. The soils were on gentle slopes (<15%) in deposits of volcanic tephra. According to Hewitt (1998), the soil in this forest is classified as Orthic Allophanic Soil or Hapludands (Soil Survey Staff 1999), having fine sandy loam texture, moderate medium crumb structure, non-sticky, non-plastic wet, very friable moist, a bulk density of 0.7 mg·m$^{-3}$ and significant quantities of allophane. The soil was air-dried and passed through a 5-mm sieve. Selected chemical properties of the soil are presented in Table 1.

**Table 1. Properties of the selected soil (depth of 0–10 cm below the litter layer) at the Kaweka forest plantation (Rivaie et al. 2008)**

| Parameter | Value |
|---|---|
| pH (1:2.5 $H_2O$) | 5.7 |
| Potassium (cmol$_c$·kg$^{-1}$) | 0.29 |
| Calcium (cmol$_c$·kg$^{-1}$) | 2.90 |
| Magnesium (cmol$_c$·kg$^{-1}$) | 0.58 |
| Sodium (cmol$_c$·kg$^{-1}$) | 0.12 |
| Carbon (%) | 5.6 |
| Nitrogen (%) | 0.27 |
| Cation exchange capacity (cmol$_c$·kg$^{-1}$) | 14 |
| Phosphorus retention (%) | 92 |
| Bray-2 P (mg·kg$^{-1}$) | 3 |
| P-total (mg·kg$^{-1}$) | 248 |

### Seed germinating

Air-dried soil (2.25 kg) (WC is 50%, equal to 1.125 kg oven-dried basis) was mixed homogeneously with the appropriate amounts of TSP. The soils were then transferred to plastic pots.

On May 5, 2001, ten broom seeds (supplied by Forest Research Ltd., Rotorua) were sown directly (after soaking 5 minutes in hot water at approximately 95ºC) into pots. After six days, the seedlings were thinned to four plants per pot.

The seeds of radiata pine (supplied by Forest Research Ltd., Rotorua) were soaked overnight in running tap water, planted in moist perlite in a box (10 cm at depth) with a lid, and kept in a dark place at 22–24ºC. Seeds began to germinate on May 5, 2001 and all the seeds germinated in eight days. Three radiata pine seedlings were transplanted into pots. After four months, a complete but –P nutrient solution (Middleton & Toxopeus 1973) was added to all pots with radiata pine seedlings. The nutrient solution was applied at a rate of 450 mL per pot during a two-week period for four times. Applications of nutrient solutions were made at 3-day interval, where soil in each pot received N of 54.2 mg·kg$^{-1}$ and K of 35 mg·kg$^{-1}$.

Soil water content was maintained at 80% by adding distilled water (field capacity of Kaweka forest soil was 87% gravimetric water content). The weight of soil in each pot at 80% field capacity was 2.59 kg. Broom weeds were harvested on September 19, 2002 (after planting the broom seedlings for 54 weeks).

### Soil and plant sampling

Soil samples were collected on September 15, 2002, from each treatment pot for the five replicates. The samples of the soil were air-dried, passed through a 2-mm sieve and stored for measuring soil plant-available P (Bray-2 P). Broom shoots were collected by cutting the plants at approximately 1 cm above the soil surface. The shoots and roots were dried in an oven at 70ºC for 48 h and the dry weights were recorded.

### Chemical analysis

The methods of chemical analysis were used according to Rivaie et al. (2008). For determination of soil pH, soil suspensions (soil: water (w/w) ratio of 1:2.5) were stirred and kept overnight at (20±2)ºC. Soil pH was determined using a pH meter equipped with a glass electrode (Blakemore et al. 1987). The organic matter content of the soils (expressed as percentage carbon) was determined by heating the samples in a stream of high purity oxygen in a Leco furnace to produce $CO_2$. The $CO_2$ was measured with an infrared detector (Leco 1996) and the quantity of gas was used to determine the total organic carbon. Cation-exchange capacity (CEC) and exchangeable cations were determined by ammonium acetate leaching at pH 7 (Blakemore et al. 1987). The concentrations of K, Ca, Mg, and Na in the leachates were determined by atomic absorption spectrometry (AAS), and the ammonium concentration was determined using an Autoanalyser (Blakemore et al. 1987).

Phosphorus retention was determined by measuring the P concentration in soil solution after 5-g soil was shaken with 25-mL solution containing P of 1000 µg·mL$^{-1}$ for 16 h. In New Zealand, Bray-2 P is the common soil test for determining P availability in soils of radiate pine plantation (Hunter et al. 1991a; Giddens et al. 1997). Bray-2 P was determined by shaking 2.5 g of air-dried soil for one minute in 25 mL of a solution containing 0.03-mol·L$^{-1}$ $NH_4F$ and 0.1-mol·L$^{-1}$ HCl and the P concentration was

measured in the solution by the colorimetric technique of Murphy & Riley (1962) (Blakemore et al. 1987).

The ground shoot and root samples were digested with a Kjeldahl digestion mixture containing 100 g of potassium sulphate and 1-g selenium powder in 1 L of concentrated sulphuric acid (95%–97%), (Twine et al. 1971). Then, the P concentrations were measured using a Technicon auto-analyser (Searle 1975; Blackmore et al. 1987).

The P concentrations in broom shoots and the dry matter yields were regressed against Bray-2 P concentration to determine the relationships between P concentrations in the broom shoot and dry matter yields with soil P availability.

### Statistical analysis

An analysis of variance (ANOVA) for a completely randomized factorial design was performed using SAS (SAS 2001). The least significant difference (LSD) test at $p < 0.05$ was used when the analysis of variance (ANOVA) results indicated that there were significant treatment effects (Steel et al. 1997). If the spread of data was proportional to the treatment mean, data were $\log_e$ transformed (Steel et al. 1997).

## Results and discussion

### Soil plant-available P

Bray-2 P concentrations were measured for determining soil plant-available P (P availability) concentrations in soils of radiata pine plantation in New Zealand (Giddens et al. 1997; Hunter et al. 1991a; Davis & Lang 1991). The soils without P fertiliser (0 $mg\cdot kg^{-1}$) had very low Bray-2 P concentrations (approximately P of 3 $\mu g\cdot g^{-1}$). Bray-2 P concentrations increased in the soil with application of P of 50 and 100 $mg\cdot kg^{-1}$ (Table 2). However, Bray-2 P concentrations with increased P fertiliser rates (50 and 100 $mg\cdot kg^{-1}$ soil) showed a small increase, which was only 2-3 $mg\cdot kg^{-1}$. One reason for this only small increase is probably due to high P fixing capacity in soil (92%, Table 1), hence, proportionately more available fertiliser-P applied was converted into less available soil P fractions (Clark & McBride 1984; Parfitt 1989). Another reason for this small increase could be greatly decreasing soil available P due to the broom taking up P (Shaben & Myers 2010).

**Table 2. Effect of P fertiliser on Bray-2 P concentration after 54 weeks of plant growth in soil in a glasshouse**

| P rate ($mg\cdot kg^{-1}$) | Bray-2 P concentration ($mg\cdot kg^{-1}$) |
|---|---|
| 0 | 3.21±0.17 z[1] |
| 50 | 6.78±0.30 y |
| 100 | 8.82±0.44 x |

**Notes**: [1]Numbers within the same column followed by the same letters are not significantly different at $p$<0.05.

The concentration of Bray-2 P in soil under broom with radiata pine was higher than that in soil under broom alone (R + B vs B) (Table 3). This suggests that the presence of radiata pine may be able to enhance P availability to the plants in P-deficient soil. The higher concentration of Bray-2 P in the former soil also indicated that the rate of P-mobilization by radiata pine roots was relatively greater than the rate of P-absorption by the radiata roots, which resulted in a higher concentration of available P in the soil of broom with radiata pine, compared with the soil of broom alone. The present result is consistent with other findings that conifers increased P availability concentrations in the soil (Davis & Lang, 1991; Davis 1995; Condron et al. 1996; Chen et al. 2000; Scott 2002; Chen et al. 2003). The increased available P concentrations in soil is probably related to organic anions (especially oxalate) released by ectomycorrhizal roots of radiata pine (Fox & Comerford 1992; DeLucia et al. 1997). Furthermore, Liu et al. (2004) in their pot trial investigated the mobilisation of soil P in the rhizosphere of radiata pine seedlings in an Allophanic soil and reported that the increase of P availability in the soil was associated with increase in acid phosphatase activity.

**Table 3. Effect of plant combination on Bray-2 P concentration after 54 weeks of plant growth in soil in a glasshouse**

| Plant combination | Bray-2 P concentration ($mg\cdot kg^{-1}$) |
|---|---|
| B[2] | 5.62 ± 0.25 y[1] |
| B+R[3] | 6.92 ± 0.32 x |

**Notes**: [1]Numbers within the same column followed by the same letters are not significantly different at $p$<0.05; "B[2]" is Broom alone; "B+R[3]" is Broom grown with radiata pine.

### Plant P concentration

The effects of phosphorus fertiliser rates and interaction between phosphorus fertiliser rates and plant combination on P concentrations of broom shoot were significant at $p$=0.0009 and $p$=0.0171, respectively. But there was no effect of different treatments on P concentration of broom root. The P concentration of broom shoot alone was marginally higher that of broom with radiata pine at the 50 $mg\cdot kg^{-1}$ soil rate (Table 4). At soil with phosphorus fertiliser (0 and 100 $mg\cdot kg^{-1}$), there was no significant difference in P concentration from broom shoot whether broom was grown alone or with radiata pine. However, the dry matter yields of boom root and shoot were significantly higher when broom was grown with radiata pine at all P fertiliser rates (Table 5).

P concentrations in broom shoots increased with P fertiliser rates whether broom was grown alone or in association with radiata pine (Table 4). This is probably related to the increase of available P concentration in soil with the increasing rates of P applied. The significant effect of P fertiliser on the increase of shoot P concentration is most probably due to the very low available P concentration in soil at the addition of 0 $mg\cdot kg^{-1}$. Shaben & Myers (2010) found that broom and Garry oak savannah ecosystem had a significant depletion effect in soil available P. This result confirmed Williams's (1981) findings that broom reaches optimum growth rates in soils with a high level of inorganic P to support its ability to fix N, grows rapidly and sets large amount

of seed. These abilities make it to be a very successful pioneer in new habitats.

**Table 4. Effect of TSP fertilizer rates on P concentration (%) in broom after 54 weeks of plant growth in a glasshouse**

| P rate ($mg \cdot kg^{-1}$) | Plant part | | | |
|---|---|---|---|---|
| | Shoot | | Root (*lsd* $_{(p<0.05)}$ = *ns*) | |
| | $B^2$ | $B+R^3$ | $B^2$ | $B+R^3$ |
| 0 | 0.057 x Y[1] | 0.064 x Y | 0.037 | 0.041 |
| 50 | 0.079 x X | 0.068 y Y | 0.037 | 0.034 |
| 100 | 0.077 x X | 0.084 x X | 0.035 | 0.038 |

**Notes**: [1]Numbers within the same column followed by the same capital letters (P rate) for each plant part or within the same row followed by the same lower case letters (plant part) are not significantly different at $p<0.05$; "B[2]" is Broom alone; "B+R[3]" is Broom grown with radiata pine.

### Dry matter yield

The responses of increasing dry matter weight from broom shoot, root and whole plant were significant ($p$ < 0.0001) to increasing P rates. Plant combination (broom alone and boom with radiata pine) also had significant effects on dry matter weights of broom shoot, root and whole plant ($p$<0.0001; $p$<0.0001; $p$<0.0001, respectively). There was a significant ($p$=0.0019) interaction effect between P fertilizer rate and plant combination on dry matter of broom root but not on broom shoot and whole plant. The dry matter of Shoot, root and whole plant increased approximately two fold in soil with P of 50 $mg \cdot kg^{-1}$ and five fold in soil with P of 100 $mg \cdot kg^{-1}$, compared with the control treatment (0 $mg \cdot kg^{-1}$ soil) (Table 5). The increase of dry matter yields is consistent with the increase of available P in soil (Table 2) and P concentration from broom shoot (Table 4) at increased P fertiliser rates. This suggested that broom removed much of the available P in the soil at the two high P rates. As broom grows vigorously at the addition of P (50 and 100 $mg \cdot kg^{-1}$) in soil (high P fertile), it may compete with radiata pine for P and probably other nutrients as well as. It was shown by others (Watt et al. 2003c) that broom can compete with radiata pine for N. The present results are also in line with the finding of a study conducted by Williams (1981). He found that broom seedlings responded readily to the addition of superphosphate (equivalent to 9 $kg \cdot ha^{-1}$).

**Table 5. Effect of TSP fertiliser on dry matter yields of shoot, root, and whole plant ($g \cdot pot^{-1}$) after 54 weeks of broom growth in a glasshouse**

| P rate ($mg \cdot kg^{-1}$) | Total dry matter yields ($g \cdot pot^{-1}$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | P rate main effect | | | P rate × plant combination interaction effect | | | | | |
| | Shoot[2] | Root[2] | Total[2] | Shoot[2] $B^3$ | Shoot[2] $B+R^4$ | Root[2] $B^3$ | Root[2] $B+R^4$ | Total[2] $B^3$ | Total[2] $B+R^4$ |
| 0 | 4.1 Z[1] | 4.0 Z | 8.1 Z | 3.0 | 5.2 | 3.4 y Z | 4.5 x Z | 6.4 | 9.7 |
| 50 | 9.6 Y | 8.9 Y | 18.5 Y | 7.9 | 11.3 | 7.2 y Y | 10.7 x Y | 15.1 | 22 |
| 100 | 22.3 X | 19.2 X | 41.5 X | 15.7 | 29.0 | 12.4 y X | 26.0 x X | 28.1 | 55 |
| Mean | | | | 8.8 y | 15.1 x | | | 16.5 y | 28.9 x |

**Notes**: [1]Numbers within the same column followed by the same capital letters (P rate) for each plant part or within the same row, followed by the same lower case letters (plant combination) are not significantly different at $p<0.05$; [2]Statistical analysis is performed on $\log_e$ (Y) transformed data; "B[3]" is Broom alone; "B+R[4]" is Broom grown with radiata pine.

When broom was grown with radiata pine, dry matter weights of the shoot, root and total broom were much higher than the corresponding weights of broom alone at all P rates (Table 5). These results are consistent with the increase of plant-available P in the soil with radiata pine seedlings (Table 3). Therefore, plant-available P from broom with radiata pine in the soil was significantly higher than that of broom alone, especially at the addition of P (50 and 100 $mg \cdot kg^{-1}$). This suggests that the presence of radiata pine enhanced P availability in the soil.

Relationships of Bray-2 P and plant P

P concentrations of broom shoot had a highly significant logarithmic relationship with Bray-2 P concentrations when broom was grown alone ($R^2$ = 0.62, $p$=0.0025), and a marginally significant linear relationship when broom was grown with radiata pine ($R^2$ = 0.34, $p$=0.0487), (Fig. 1).

According to Mehlich (1978), the Bray-2 P extractant (0.03 $mol \cdot L^{-1}$ $NH_4F$ + 0.1 $mol \cdot L^{-1}$ HCl) is known to dissolve P associated with Ca, Fe, and Al. In the present study, the result showed that P concentration from broom shoot is related to Bray-2 P. This indicates that broom is taking up P from one or more of these P pools. The relationship of P concentrations from broom shoot and Bray-2 P concentrations suggests that the increase in P concentrations from broom shoot diminished with an increase in the soil plant-available P concentration.

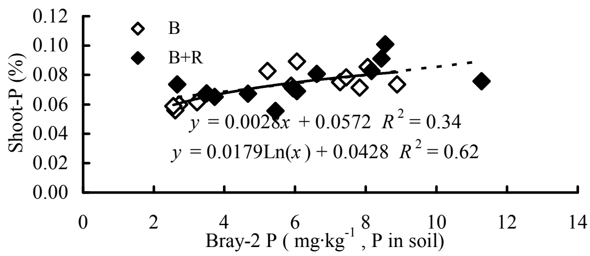


**Fig. 1 Relationships between P concentration from broom shoot and Bray-2 P concentration after 54 weeks of plant growth in a glasshouse.** "B" is soil from broom alone. "B+R" is soil from broom with radiata pine.

Relationship of Bray-2 P and dry matter

The relationship of broom dry matter weight and Bray-2 P concentration fitted to an exponential equation. The total broom dry matter weight showed a significant exponential relationship with Bray-2 P concentration in soils with broom alone ($R^2$ = 0.86; $p$<0.0001), as well as when broom was grown with radiata pine ($R^2$ = 0.84; $p$<0.0001) (Fig. 2). The data show that for a fixed Bray-2 P concentration, broom growing with radiata pine had a higher dry matter yield than broom growing alone.

The exponential relationships probably suggest that broom has a higher external efficiency of P utilisation at the higher rate of P application (medium to high P fertile soils). The broom root weight doubled when P rate increased from 50 to 100 mg·kg$^{-1}$ in soil (Table 5). The great increase in broom root weight is most probably due to the increased N fixation by broom with the increased P availability in the soil. In accordance with the present result, Binkley et al. (2003) also found that the rates of growth and N fixation of *Facaltaria* seedlings were limited by the supply of P in the soils.

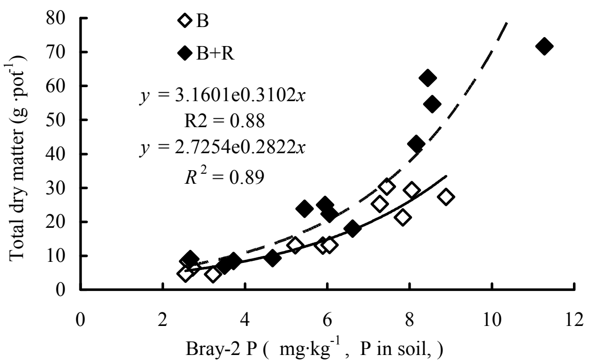


**Fig. 2 Relationships between total broom dry matter weight and Bray-2 P concentration after 54 weeks of plant growth in a glasshouse.** “B” is soil from broom alone. “B+R” is soil from broom with radiata pine.

## Conclusions

Phosphate fertiliser application increased P availability in the soil as measured by Bray-2 P concentrations. The P availability concentration in the soil of broom growing in association with radiata pine seedlings was higher than that in soil of broom growing alone. The increased soil plant-available P is most probably related to the organic anions, especially oxalate and the acid phosphatase enzyme released by radiata pine roots. The present result provided evidence of a beneficial effect of radiata pine on soil P availability.

The P concentration and the dry matter yield of broom shoot increased with the application of increased rates of TSP in a P-deficient Allophanic Soil. Broom grows vigorously in high P fertile soils; hence, it may compete with radiata pine for P and other nutrients. When broom was grown in the presence of radiata pine, the broom dry matter yield was much higher than that of broom alone at all P rates. This is probably that the plant-available P concentration in the soil of broom with *P. radiata* was significantly higher than that of broom alone; suggesting that the presence of radiata pine enhanced P availability to the associated plant.

The P concentrations from broom shoot had a highly significant logarithmic relationship with Bray-2 P concentrations. This indicates that broom is taking up P from one or more of the P pools, such as Ca-P, Fe-P and Al-P. The curvilinear relationship of P concentrations from broom shoot with Bray-2 P concentrations suggests that P concentrations in broom shoot diminished with an increase in the Bray-2 P concentration in the soil. Furthermore, the dry matter yield of broom showed a significant exponential relationship with Bray-2 P concentration. The data show that for a fixed Bray-2 P concentration, broom growing with radiata pine had a higher dry matter yield than broom growing alone, especially at the application of high P rates. This could be due to the higher N fixed by the broom at these high levels of P in soil, which resulted in the greater dry matter, especially the root yield.

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## References

Binkley D, Giardina C, Bashkin MA. 2000. Soil phosphorus pools and supply under the influence of *Eucalyptus saligna* and nitrogen-fixing *Albizia falcataria*. *Forest Ecology and Management*, **128**: 241−247.

Binkley D, Senock R, Cromack JrK. 2003. Phosphorus limitation on nitrogen fixation by Facaltaria seedlings. *Forest Ecology and Management*, **186**: 171−176.

Blakemore LC, Searle PL, Day BK. 1987. *Methods for chemical analysis of soils*. Lower Hutt, New Zealand: New Zealand Soil Bureau, Scientific Report, NZ Soil Bureau, p. 80.

Chen CR, Condron LM, Davis MR, Sherlock RR. 2000. Effects of afforestation on phosphorus dynamics and biological properties in a New Zealand grassland soil. *Plant and Soil*, **220**: 151−163.

Chen C R, Condron L M, Sinaj S, Davis MR, Sherlock RR, Frossard E. 2003. Effects of plant species on phosphorus availability in a range of grassland soils. *Plant and Soil*, **256**: 115-130.

Clark CJ, McBride MB. 1984. Cation and anion retention by natural and synthetic allophane and imogolite. *Clays and Minerals,* **22**: 291−299.

Clinton PW, Frampton CM, Mead DJ. 1994. Modelling competitive pasture effects on nutrient uptake by *Pinus radiata*. *New Zealand Journal of Forestry Science*, **24**: 268−278.

Condron LM, Davis MR, Newman RH, Cornforth S. 1996. Influence of conifers on the forms of phosphorus in selected New Zealand grassland soils. *Biology and Fertility of Soils*, **21**: 37−42.

Davis MR. 1995. Influence of radiata pine seedlings on chemical properties of some New Zealand montane grassland soils. *Plant and Soil*, **176**: 255−262.

Davis MR, Lang MH. 1991. Increased nutrient availability in topsoils under

conifers in the South Island high country. *New Zealand Journal of Forestry Science*, **21**: 165–179.

DeLucia EH, Callaway RM, Thomas EM, Schlesinger WH. 1997. Mechanisms of phosphorus acquisition for ponderosa pine seedlings under high $CO_2$ and temperature. *Annals Botany*, **79**: 111–120.

Fogarty G, Facelli JM. 1999. Growth and competition of *Cytisus scoparius*, an invasive shrub, and Australian native shrubs. *Plant Ecology*, **144**: 27–35.

Fox TR, Comerford NB. 1992. Influence of oxalate loading on phosphorus and aluminum solubility in Spodosols. *Soil Science Society of America Journal*, **56**: 290–94.

Gadgil RL, Charlton JFL, Sandberg AM, Allen PJ. 1992. Nutritional relationships between pampas grass (*Cortaderia* spp.) and *Pinus radiata*. *New Zealand Journal of Forestry Science*, **22**: 3–11.

Giddens KM, Parfitt RL, Percival HJ.1997. Comparison of some soil properties under *Pinus radiata* and improved pasture. *New Zealand Journal of Agricultural Research*, **40**: 409–416.

Hewitt AE. 1998. *New Zealand soil classification*. Landcare research science series No. 1. Lincoln, New Zealand: Manaaki Whenua Press, Landcare Research New Zealand Ltd., p. 133.

Hunter IR, Hunter JAC. 1991a. Apparent phosphorus uptake and change in nitrogen content of *Pinus radiata* growing on soils of different phosphorus retention, treated with superphosphate and A-grade rock phosphate. *New Zealand Journal of Forest Science*, **21**: 50–61.

Hunter IR, Rodgers BE, Dunningham A, Prince JM, Thorn AJ. 1991b. *An atlas of radiata pine nutrition in New Zealand*. Rotorua, New Zealand: New Zealand Ministry of Forestry. FRI Bulletin No. 165, 24 pp.

Leco Corporation. 1996. CNS-2000 Elemental Analyzer - Instruction Manual. St. Joseph (MI): LECO Corporation, p. 25.

Liu Q, Loganathan P, Hedley MJ, Skinner MF. 2004. The mobilisation and fate of soil and rock phosphate in the rhizosphere of ectomycorrhizal *Pinus radiata* seedlings in an Allophanic Soil. *Plant and Soil*, **264**: 219–229.

MacLaren JP. 1993. *Radiata Pine Growers' Manual*. New Zealand: New Zealand Forest Research Institute, Rotorua. FRI Bulletin No.184.

Mason EG, Milne PG. 1999. Effects of weed control, fertilization, and soil cultivation on the growth of *Pinus radiata* at midrotation in Canterbury, New Zealand. *Canadian Journal of Forest Research*, **29**: 985–992.

Mehlich A. 1978. Influence of fluoride, sulfate and acidity on extractable phosphorus, calcium, magnesium and potassium. *Communication in Soil Science and Plant Analysis*, **9**: 455–476.

Middleton KR, Toxopeus MRJ. 1973. Diagnosis and measurement of multiple soil deficiencies by a substractive technique. *Plant and Soil*, **38**: 219–226.

Nielsen ET, Karpa, D, Mooney HA, Field C. 1993. Patterns of stem photosynthesis in two invasive legumes (*Spartium junceum, Cytisus scoparius*) of the California coastal region. *American Journal of Botany*, **80**: 1126–1136.

O'Connell AM, Grove TS. 1996. Biomass production, nutrient uptake and nutrient cycling in the Jarrah (*Eucalyptus marginate*) and Karri (*Eucalyptus diversicolor*) forests of South-western Australia. In: PM Attiwill and MA Adams (eds), *Nutrition of Eucalyptus*. Victoria, Australia: CSIRO Australia, pp. 155–190.

Parfitt RL. 1989. Phosphate reactions with natural allophane, ferrihydrite and goethite. *Journal of Soil Science*, **40**: 359–369.

Parker IM. 2000. Invasion dynamics of *Cytisus scoparius*: a matrix model approach. *Ecological Applications*, **10**: 726–743.

Partridge TR. 1992. Successional interactions between bracken and broom on the Port Hills, Canterbury, New Zealand. *Journal of Applied Ecology*, **29**: 85–91.

Paynter Q, Downey PO, Sheppard AW. 2003. Age structure and growth of the woody legume weed *Cytisus scoparius* in native and exotic habitats: implications for control. *Journal of Applied Ecology*, **40**: 470–480.

Peterson DJ, Prasad R. 1998. The biology of Canadian weeds. 109. *Cytisus scoparius* (L.) Link. *Canadian Journal of Plant Science*, **78**: 497–504.

Richardson B, Vanner A, Ray J, Davenhill N, Coker G. 1996. Mechanisms of *Pinus radiata* growth suppression by some common forest weed species. *New Zealand Journal of Forestry Scienc*e, **26**(3): 421–437.

Rivaie AA, Loganathan P, Graham JD, Tillman RW, Payn TW. 2008. Effect of phosphate rock and triple superphosphate on soil phosphorus fractions and their plant-availability and downward movement in two volcanic ash soils under *Pinus radiata* plantations in New Zealand. *Nutrient Cycling in Agroecosystems*, **82**: 75–88.

Roy B, Popay I, Champion P, James T, Rahman A. 1998. *An illustrated guide to common weeds of New Zealand*. Canterbury, Rotorua, New Zealand: New Zealand Plant Protection Society (Inc), p.314.

SAS. 2001. *Instruction Manual*. North Carolina, USA: SAS Institute Inc., Cary, North Carolina, USA. p. 335.

Scott JT. 2002. Soil Phosphorus Dynamics in a Temperate Silvopastoral System. PhD Thesis. Lincoln University, Lincoln: New Zealand, p. 294.

Searle PL. 1975. Automated colorimetric determination of ammonium ions in soil extracts with 'Technicon Autoanalyser II equipment'. *New Zealand Journal of Agricultural Research*, **18**: 183–187.

Shaben J, Myers JH. 2010. Relationships between Scotch broom (*Cytisus scoparius*), soil nutrients, and plant diversity in the Garry oak savannah ecosystem. *Plant Ecology*, **207**(1): 81–91.

Soil Survey Staff. 1999. *Soil Taxonomy*. A basic system of soil classification for making and interpreting soil surveys (2nd edition). Washington DC, USA: Agricultural Handbook 436, Natural Resources Conservation Service, USDA, p. 869.

Steel RGD, Torrie JH, Dickey DA. 1997. Analysis of Variance IV. Split-plot Design and Analysis. In: *Principle and Procedures of Statistics: a Biometrical Approach*, (3rd edition). New York, USA: The McGraw-Hill Companies, Inc., p. 672.

Tabard P. 1985. Une plante energetique a cycle court. Le genet: *Cytisus scoparius*. In: *Energy from biomass*. (Eds. W Palz, J Coombs, DO Hall). London, England: Applied Science, London, pp. 283–291.

Twine JR, Williams CH. 1971. The determination of phosphorus in kjeldahl digests of plant materials by automatic analysis. *Communication in Soil Science and Plant Analysis*, **2**: 485–489.

Watt MS, Whitehead D, Richardson B, Mason EG, Leckie AC. 2003a. Modelling the influence of weed competition on the growth of for light and water on growth of young *Pinus radiata* at a dryland site. *Forest Ecology and Management*, **178**: 271–286.

Watt MS, Whitehead D, Mason EG, Richardson B, Kimberley MO. 2003b. The influence of weed competition for light and water on growth and dry matter partitioning of young *Pinus radiata,* at a dryland site. *Forest Ecology and Management*, **183**: 363–376.

Watt MS, Clinton PW, Whitehead D, Richardson B, Mason EG, Leckie AC. 2003c. Above-ground biomass accumulation and nitrogen fixation of broom (*Cytisus scoparius* L.) growing with juvenile *Pinus radiata* on a dryland site. *Forest Ecology and Management*, **184**: 93–104.

Williams PA. 1981. Aspects of the ecology of broom (*Cytisus scoparius*) in Canterbury, New Zealand. *New Zealand Journal of Botany*, **19**: 31–43.

Zou X, Binkley D, Caldwell BA. 1995. Effects of dinitrogen-fixing trees on phosphorus biogeochemical cycling in contrasting forests. *Soil Science of American Journal*, **59**: 1452–1458.